MANNED SPACECRAFT CENTER

INTERNAL NOTE NO. MSC-IN-65-EP-20

TEST EVALUATION OF THE EFFECT OF FLUID TEMPERATURE

ON CRYOGENIC VESSEL HEAT LEAK UTILIZING SEVERAL MEASUREMENT TECHNIQUES

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INTRODUCTION

The purpose of this test program was to establish the effect of fluid temperature on indicated heat leak (previously available data indicates a decreasing heat leak with decreasing fluid temperature) and to compare the results of alternate methods of heat leak determination. Liquid oxygen, liquid nitrogen, and liquid helium were the test cryogens. Vented weight loss tests and ambient heat leak pressurization tests were conducted with each cryogen. In addition, a minimum flow rate test was conducted using oxygen.

The test dewar used in this program was a Gemini 14-day ECS primary oxygen subsystem.

The tests were conducted by the Power Systems Test Section of the Thermochemical Test Branch for the Thermodynamic Power Section of the Power Generation Branch, Propulsion and Power Division. The program was conducted at the Power Systems Test Facility, Building 354, during the period from August 19, 1965 through September 25, 1965, in response to Thermochemical Test Request Number EP631-421.

TEST ARTICLE DESCRIPTION

The dewar used during this test program was a Gemini 14-day ECS primary O_2 subsystem. The subsystem normal operating pressure is 850 $^{+60}_{-50}$ psig and the maximum operating pressure is 1000 psig at -160°F. The rated oxygen capacity is 106 pounds total and 104 pounds useful. The inner vessel volume is 1.65 ft^3 which corresponds to a maximum oxygen weight of 117 pounds. The vent port is positioned to allow fill only to the rated oxygen capacity of 106 pounds which is equivalent to 1.49 ft^3. This rated oxygen capacity corresponds to a nitrogen capacity of 75 pounds and a helium capacity of 11.6 pounds.

The inner vessel is constructed of Inconel and is 17.60" I.D. The outer vessel is constructed of Titanium and is 20.06" O.D. The annular space is approximately 1 1/8" thick. The inner vessel is wrapped with 50 layers of aluminized mylar insulation. The subsystem contains a quantity gaging system and a resistance temperature probe. A cross sectional view of the test dewar is shown in figure 1.

TEST PROGRAM

The test program consisted of a heat leak evaluation using liquid oxygen, liquid nitrogen, and liquid helium. A vented weight loss test and an ambient heat leak pressurization test were conducted using each cryogen. A minimum flow rate test was also conducted using oxygen. Seven tests were accomplished as follows:

Test	Cryogen	Procedure
1	Oxygen	Ambient heat leak pressurization
2	Oxygen	Vented weight loss test
3	Oxygen	Minimum flow rate
4	Nitrogen	Ambient heat leak pressurization
5	Nitrogen	Vented weight loss test
6	Helium	Ambient heat leak pressurization
7	Helium	Vented weight loss test

TEST SETUP DESCRIPTION

System cleanliness, for oxygen service, had been previously verified in
a preceeding test program. The dewar was maintained in a pressurized
condition and all entering fluid was filtered to obviate additional oxygen
cleaning.

The liquid oxygen and liquid nitrogen was transferred from facility storage
dewars to the test dewar through a 25 micron (absolute) filter and a 1/2"
diameter foam insulated transfer line. The facility storage dewars were
pressurized to approximately 25 psig and the test dewar was maintained at
a pressure of approximately 3 psig during transfer operations.

The liquid helium was delivered to the test facility in vendor-supplied
100 liter dewars. The liquid helium was transferred to the test dewar
through a 1/4" diameter vacuum insulated transfer hose. The liquid helium
was transferred with a supply dewar pressure of 6 psig and a test dewar
pressure of 1 psig.

The test dewar was mounted in a test support fixture which allowed 180°
dewar rotation. The test dewar was rotated in order to mix the cryogen
and thereby minimize temperature stratification following pressurization.
Figure 2 pictorally illustrates the test setup. Figures 3 and 4 are sche-
matic representations of the instrumentation and fluid flow systems.

Throughout each test, the following parameters were continuously recorded
on a multipoint recorder: vent gas temperature, fluid temperature, fluid
weight, outer shell temperature (3 each), flow meter temperature, ambient
temperature, flow rate, and percent fill. The capacitance values of the
quantity probe were read and manually recorded at two (2) hour intervals
utilizing a capacitance bridge measurement system.

The primary means of measuring the vent rate during the vented weight loss
tests and minimum flow rate test was with a differential pressure flow meter.
The output of the differential pressure flow meter was recorded on the multi-
point recorder. Additional methods of measuring fluid loss rate were used
to provide redundant measurements on the same test. The backup measurement
methods consisted of a weigh system which indicated the remaining fluid
weight, a wet test flow meter, and a capacitance probe quantity gaging
system. The weigh system was calibrated prior to each test but hysteresis
effects caused by the flexible fluid flow lines on the test dewar may have
caused slight inaccuracies. The wet test flow meter and the capacitance
quantity gaging system were not calibrated prior to each run and therefore
were not considered as accurate as the differential pressure flow meter
and the weigh system.

A resistance type temperature probe was installed in the vent port in order
to determine the amount of sensible heat added to the gas as it passed through
the annulus. The probe was located approximately 3/4" downstream of the vent
line penetration of the outer shell. Although the vent line was insulated
in the area of the temperature probe, the ambient temperature probably con-

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tributed to a higher vent gas temperature. Ideally, this probe should
be located slightly upstream of the outer shell penetration. A resis-
tance type temperature probe located in the inner vessel indicated the
fluid temperature during the oxygen and nitrogen test. This internal
temperature probe, an integral part of the test dewar, was designed for
oxygen service and did not offer reliable data in liquid helium service.

The dewar pressure was indicated by both a mechanical test gage and a
strain gage pressure transducer. Strain gage pressure transducers
ranging from 0-5 psig, 0-100 psig, or 0-1000 psig were used, depending
on the test program in progress.

TEST PROCEDURES

For the liquid nitrogen and oxygen test, the dewar was filled with the test cryogen at least 24 hours prior to test in order to allow adequate thermal stabilization. In the case of liquid helium, the high boil-off rate precluded holding helium for 24 hours.

Vented Weight Loss Test Procedure

The dewar was refilled ("topped off") to maximum capacity and allowed to vent at ambient pressure until the internal temperature probe indicated a stable temperature (generally 6 to 8°F degrees above boiling point temperature). The dewar was then allowed to vent through the differential pressure flow meter. The wet test flow meter, capacitance probe, and weigh system were used during the oxygen and nitrogen vented weight loss test programs to provide comparative vent rate data. The wet test meter and the weigh system were not utilized in the helium testing due to the high vent rate and the plumbing configuration. The dewar was not rotated during the vented weight loss test.

Minimum Flow Rate Test Procedure

Only one minimum flow rate test was conducted (Test 3 with liquid oxygen). Prior to initiating this test, the test dewar was "topped off" and allowed to vent until an average fluid density of 38 lb/ft^3 was obtained. The dewar was than pressurized to operating pressure (850 psig) by cyclic operation of the emergency internal heaters. The system was rotated following pressurization to eliminate temperature stratification. The minimum vent rate, at which an operating pressure of 850 psig could be maintained was then established. The vent rate was controlled with a manual metering valve downstream of the differential pressure flow meter. The weight loss was also measured by the weigh system and the quantity gaging system.

Ambient Heat Leak Test Procedure

The test dewar was "topped off" and allowed to vent to 97 per cent of rated O_2 volumetric capacity (1.45 ft^3) for each cryogen. At this time, the vent was closed and the dewar was allowed to pressurize from heat leak. The fluid quantity for the N_2 and He test were determined by the weigh system since the quantity probe was designed for oxygen service. Each cryogen was pressurized by ambient heat leak to above the cryogen's critical pressure (O_2 = 737 psia, N_2 = 491 psia, and He = 33 psia). For the oxygen and nitrogen test, after reaching 850 psig for oxygen and 600 psig for nitrogen, the dewar was rotated to allow mixing of the cryogen in order to eliminate temperature stratification. The ambient heat leak pressurization continued after the rotation until the original test pressure was again attained. Following this, the dewar was vented. The dewar was not rotated following the helium ambient heat leak pressurization since it was necessary that the vacuum insulated transfer line remain attached during pressurization and the lack of transfer line flexibility prevented dewar rotation.

RESULTS AND DISCUSSION

Test 1 - The oxygen ambient heat leak pressurization resulted in a pressure buildup from 0 psig to 850 psig in 119 hours. The dewar evidenced a pressure decay of 20 psig when rotated at 850 psig, indicating minor temperature stratification. The system was allowed to repressurize to 850 psig following rotation. The test was concluded following this repressurization. The total fluid weight was 102 pounds which corresponds to an average fluid density of 61.8 lb/ft^3. The break in the pressure buildup curve indicated that the fluid changed from the two-phase region to the compressed liquid region at 153 psia and $212^{\circ}R$. If a constant density pressurization is assumed, the fluid should pass into the compressed liquid region at 125 psia. This deviation between actual and theoretical pressures for entering the compressed liquid region is probably due to temperature stratification and/or accumulated instrumentation error. The indicated heat leak, based on the change in internal energy from 0 psig to 850 psig, was 18.4 BTU/hr (Appendix). Figure 5 illustrates the pressure buildup rates.

Test 2 - The oxygen vented weight loss test was conducted over a 140 hour period. The fluid quantity decreased from 89 percent fill to 65 percent fill during this time. The internal temperature probe indicated $-288^{\circ}F$ and the vent temperature indicated $+35^{\circ}F$ during the vented weight loss test. This indicated vent gas temperature was considered somewhat high since the temperature probe was located approximately 1" downstream of the outer shell allowing the ambient temperature to unduly influence the vent gas temperature. The indicated weight loss rates were as follows: 0.207 lb/hr based on the differential pressure flow meter, 0.191 lb/hr based on the weigh system indicated loss, 0.166 lb/hr based on the wet test meter readings, and 0.174 lb/hr based on the change in indicated percent fill. This wide range of indicated flow points out the problem of low flow rate measurement and illustrates the problem of acceptance or rejection of a system based on this measurement. The value of 0.207 lb/hr from the differential pressure flow meter is considered to be the most accurate. The heat leak, based on a weight loss of 0.207 lb/hr considering latent heat only, is 19 BTU/hr.

Test 3 - During the oxygen minimum flow rate test, the average fluid density decreased from 38.0 lb/ft^3 to 14.4 lb/ft^3. Figure 6 illustrates the minimum flow rate versus average fluid density. As is evident in figure 6, the greatest flow rate was required in the density range of 22 to 28 lb/ft^3. The greatest flow, to maintain a constant dewar pressure, occurs at the lowest point on the specific heat input (BTU/lb of fluid expelled) versus average fluid density (lb/ft^3) curve. Theoretically the greatest flow should occur at a density of 24 lb/ft^3 which represents the low point on the specific heat input curve for 850 psig. The flow in the range from 22 lb/ft^3 to 28 lb/ft^3 was 0.355 lb/hr. Using the theoretical minimum specific heat input of 30 BTU/lb at 24 lb/ft^3, a heat leak of 10.65 BTU/hr is indicated.

Test 4 - The nitrogen ambient heat leak pressurization resulted in a pressure buildup from 0 psig to 600 psig in 80.5 hours. Test dewar rotation following the initial pressurization resulted in a 5 psig pressure decay indicating very minor temperature stratification. The system was allowed to repressurize

to 600 psig following rotation. The test was concluded following the repressurization. The total fluid weight was 73 pounds which corresponded to an average fluid density of 44.2 lb/ft^3. The break in the pressure build-up curve indicates that the fluid passed from the two-phase region into the compressed liquid region at 130 psig and 181°R. The indicated heat leak, based on the change in internal energy during the pressurization process from 0 psig to 600 psia, was 16.95 BTU/hr. Figure 7 illustrates the pressure build-up rate.

Test 5 - The nitrogen vented weight loss test was conducted over a 104 hour period during which time the percent fill decreased from 94 percent to 69 percent. The internal temperature probe indicated a fluid temperature of -311°F and the vent temperature averaged +15°F. The recorded vent rate was 0.192 lb/hr. Based on a weight loss of 0.192 lb/hr, the heat leak, considering latent heat only, was 16.9 BTU/hr.

Test 6 - The helium ambient heat leak pressurization resulted in a pressure buildup from 3 psig to 100 psig in two hours and 20 minutes. Figure 8 illustrates the pressure buildup rate. The system was not rotated for relief of temperature stratification because it was necessary that the vacuum insulated transfer line remain attached to the subsystem. The total fluid weight was 11.6 pounds resulting in an average fluid density of 7.03 lb/ft^3. As is evident in figure 8, the sharp break or change in slope of the pressurization curve experienced during the oxygen and nitrogen test was not noted. This change in slope occurs at the point where the fluid state changes from two-phase to single phase. The curve does indicate a slight change in slope starting at 15 psig. Based on the recorded fluid weight, the fluid should have entered the single phase region at 8.8 psig (v = 0.142 ft^3/lb). This discrepancy may be caused by a combination of weigh system and pressure transducer error. The indicated heat leak, based on the change in internal energy from 3 psig to 100 psig, was 16.4 BTU/hr. If the quantity of helium was less than maximum capacity of the dewar, as might be interpreted from the higher transition point, the calculated heat leak would be greater than 16.4 BTU/hr.

Test 7 - The helium vented weight loss test indicated a vent rate of 1.2 lb/hr as measured by the differential pressure flow meter. Difficulty was experienced in achieving a stable flow rate because the high loss rate depleted the liquid helium before a steady vent rate was established. The figure of 1.2 lb/hr was based on a steady flow condition for one hour 20 minutes. Based on a weight loss of 1.2 lb/hr, the heat leak, considering latent heat only, is 10.7 BTU/hr. This represents a 34.8 percent reduction in heat leak when compared with the results of Test 6. Acknowledging the possible inaccuracies associated with the limited helium testing, this reduction may be slightly high; however, it may also be indicative of the advantage of utilizing vapor-shielding on helium storage systems. The lower fluid temperature, lower latent heat of vaporization and higher specific heat characteristics of helium as compared to the other cryogens used tend to make the vapor-cooling effect more pronounced.

The preceding data indicates a decrease in the indicated heat leak as the fluid temperature decreases. Figure 9 illustrates the relationship between fluid temperature and heat leak. In the case of helium, the heat leak,
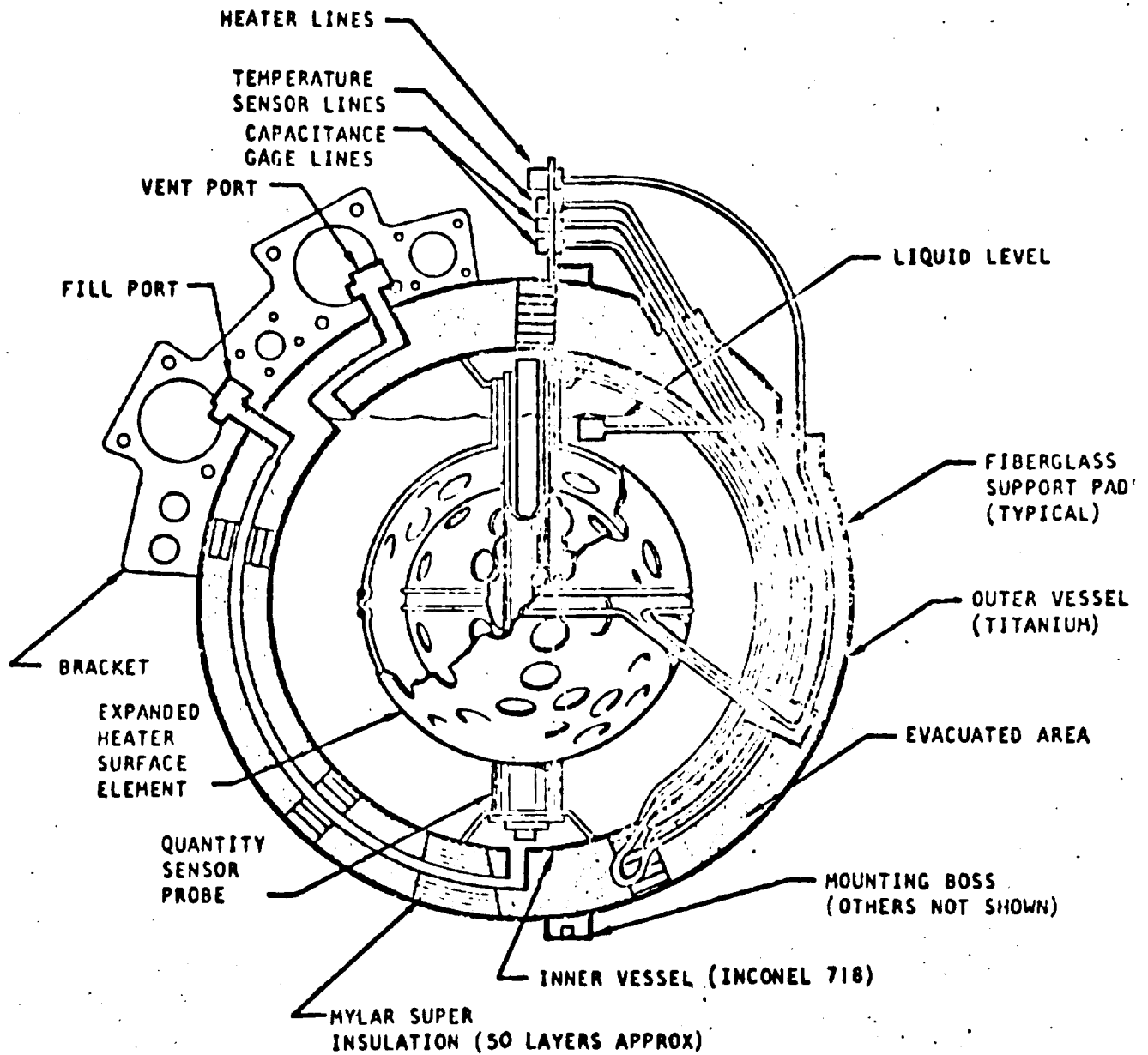
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based on the vented weight loss test, indicated a more significant decrease than the ambient heat leak pressurization test. The following factors may contribute to a decrease in the indicated heat leak as the fluid temperature decreases: decreased thermal conductivity values for support pads, fluid flow tubing, and laminar insulation; decreased absorptivity of the inner shell for radiant heat transfer; decreased annular pressure due to additional cryopumping by the colder fluid; vapor cooling produced by the colder vent gas absorbing heat from the annulus laminar insulation during flow test. These factors must be considered with respect to the greater temperature differential, which results in an increase in heat transfer, in order to arrive at the total heat transfer. The decrease in the test dewar heat leak in this program is probably attributable to the improved annular vacuum due to cryopumping for the ambient heat leak pressurization test and to the combined effects of cryopumping and vapor cooling for the vented weight loss tests. The cryopumping was probably significant because of the slightly degraded test dewar vacuum. Therefore, for test purposes, the annular vacuum must be maintained at $(1 \times 10^{-4}$ mm Hg$)$ or cryopumping of the annular vacuum becomes predominate as the means of heat leak reduction. At pressures below 1×10^{-4} mm Hg gas conduction/convection ceases to be a significant mode of heat transfer. It is reported that tests by AiResearch on similar dewars have indicated approximately a 10% increase in heat leak from oxygen to hydrogen service where the annular vacuum was maintained below 1×10^{-4} mm Hg; however, similar data on "as delivered" tanks has resulted in the same trend as noted in the MSC test.

CONCLUSIONS

1. A decrease in heat leak was noted with lower boiling point cryogens. This was probably due to an improvement in the annular vacuum caused by cryopumping. The extent of cryopumping cannot be definitely established as the test dewar did not have provisions for measuring the annular pressure.

2. The helium vented weight loss test (considering latent heat only) indicated a significantly lower heat leak than the ambient heat leak pressurization test. This is considered to be due primarily to vapor-cooling as the vent gas absorbs heat from the annulus. This heat leak reduction indicates that the effect of vapor cooling should be evaluated in the design of helium storage systems.

3. Exact heat leak values based on vented weight loss tests are difficult to substantiate because of problems associated with low flow rate measurements. Measurements based on vent flow rate and fluid weight loss are desirable for each test.

4. Calculation of sensible heat addition to the vent gas during vented weight loss tests was not meaningful during this program due to problems of accurately measuring exit gas temperature. If the vent gas temperature is to be measured, a temperature probe should be installed during the fabrication of the dewar.

5. For future tests, the annular pressure should be recorded and all tests should be made with an annular pressure below 1×10^{-4} mm Hg in order to minimize conduction/convection effects of gas in the annulus. This will eliminate the significance of cryopumping and allow an analysis of the change in thermal properties as the working temperature decreases.
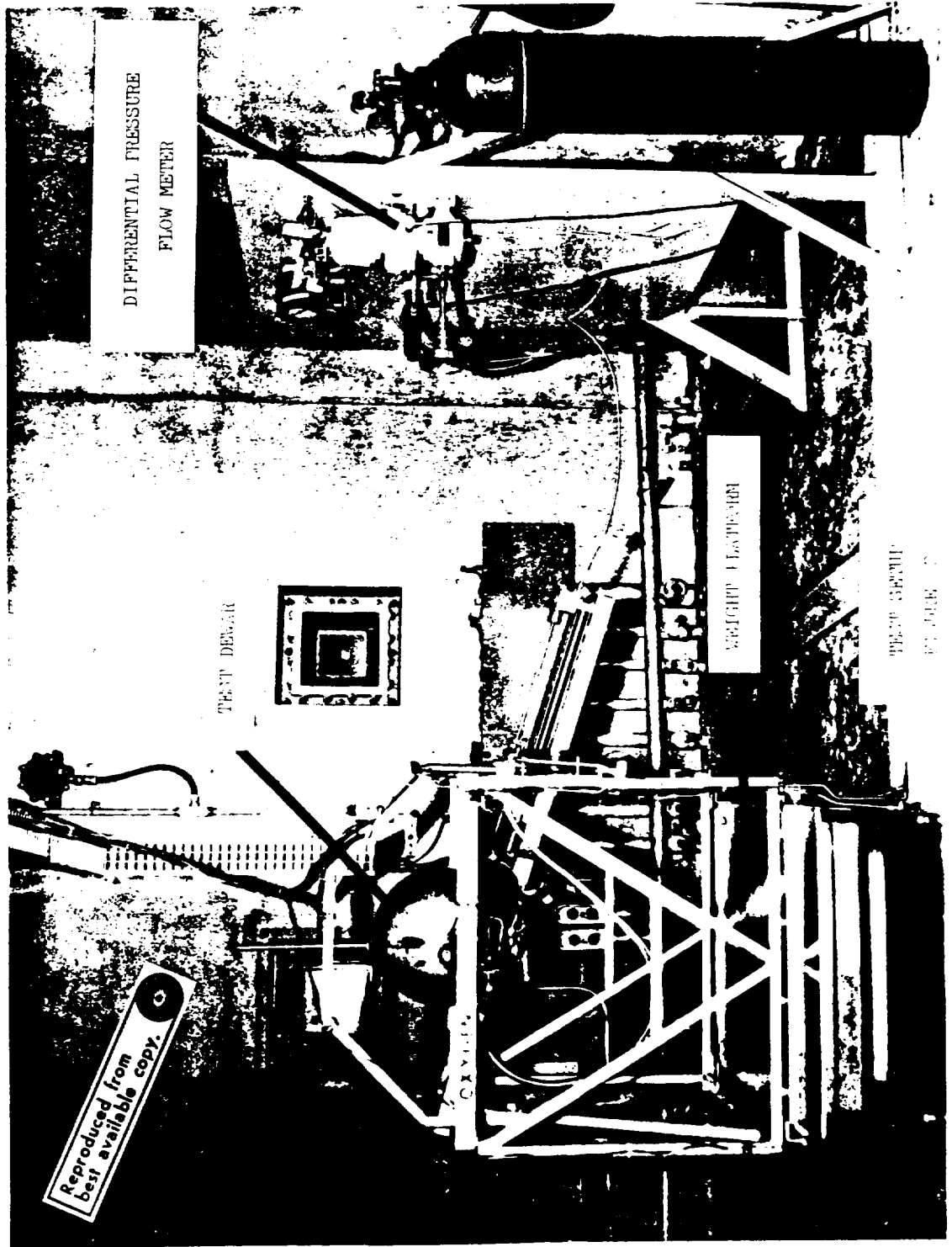
REFERENCES

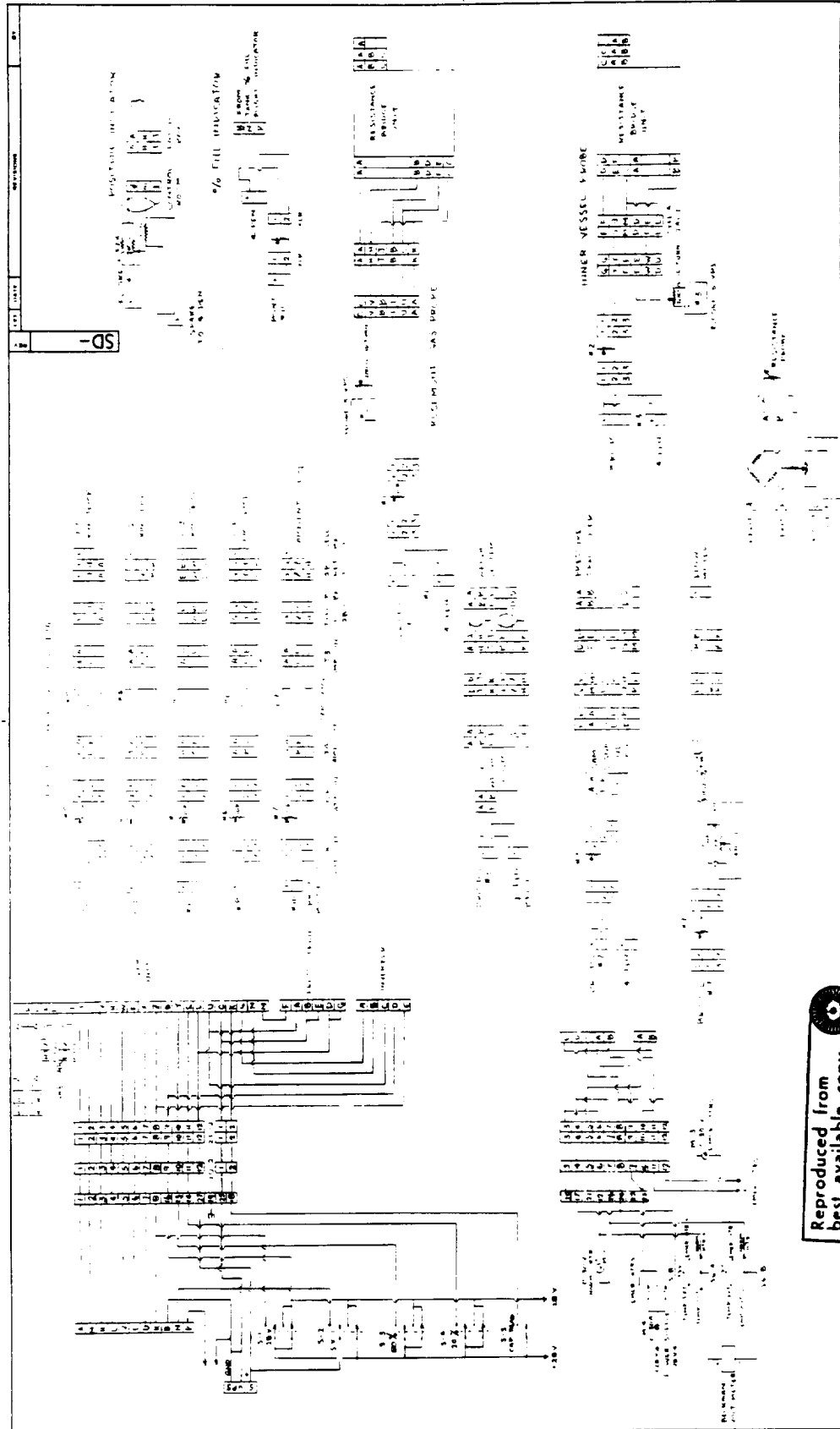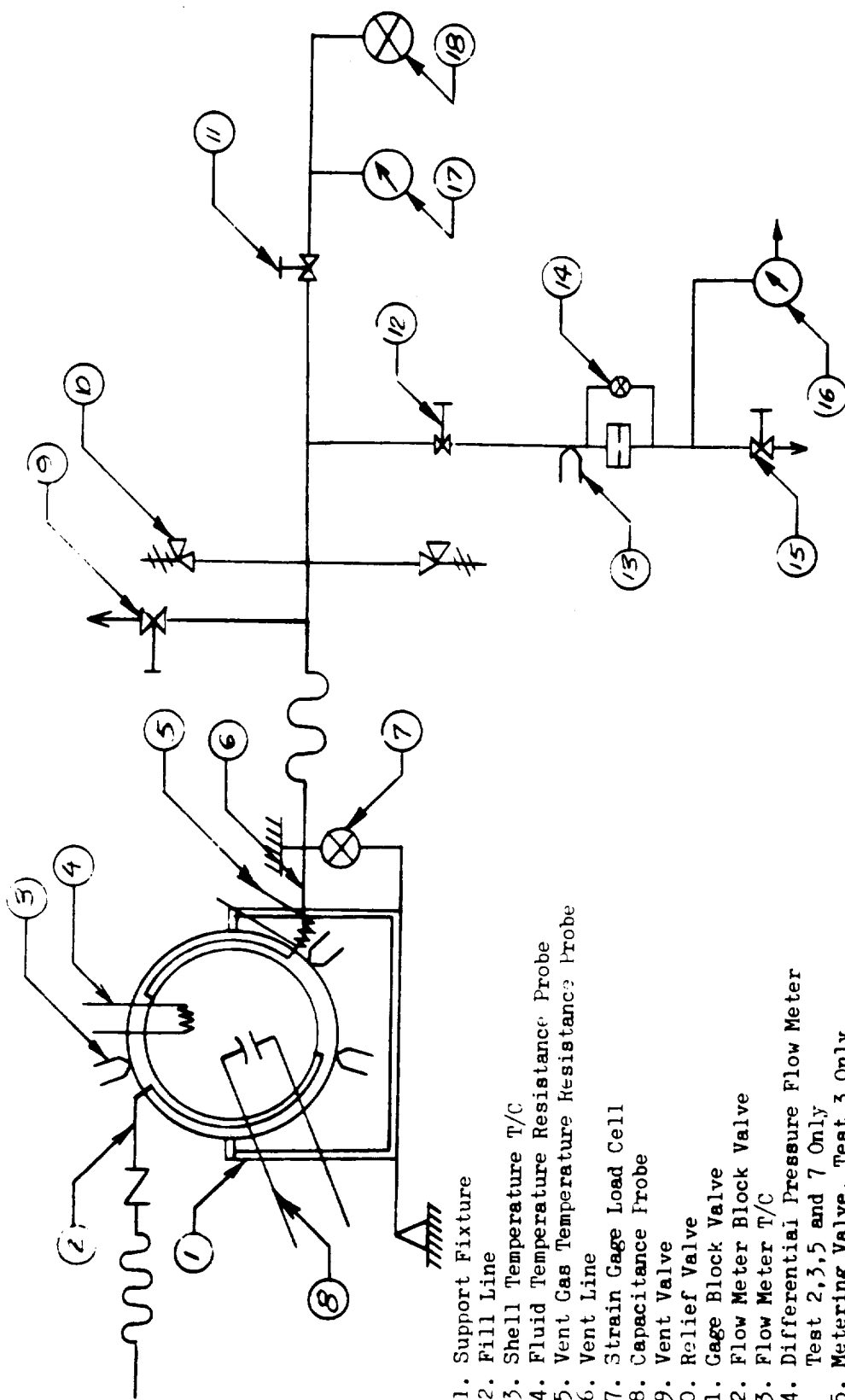1. Thermochemical Test Request EP631-421, dated July 21, 1965.

HEATER LINES

TEMPERATURE
SENSOR LINES

CAPACITANCE
GAGE LINES

VENT PORT

FILL PORT

LIQUID LEVEL

FIBERGLASS
SUPPORT PAD
(TYPICAL)

OUTER VESSEL
(TITANIUM)

EVACUATED AREA

BRACKET

EXPANDED
HEATER
SURFACE
ELEMENT

QUANTITY
SENSOR
PROBE

MOUNTING BOSS
(OTHERS NOT SHOWN)

INNER VESSEL (INCONEL 718)

MYLAR SUPER
INSULATION (50 LAYERS APPROX)

TEST DEWAR

FIGURE 1

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DIFFERENTIAL PRESSURE FLOW METER

TEST DEWAR

WEIGHT PLATFORM

TEST SETUP

PAGE 13

INSTRUMENTATION SCHEMATIC
FIGURE 3
PAGE 14

1. Support Fixture
2. Fill Line
3. Shell Temperature T/C
4. Fluid Temperature Resistance Probe
5. Vent Gas Temperature Resistance Probe
6. Vent Line
7. Strain Gage Load Cell
8. Capacitance Probe
9. Vent Valve
10. Relief Valve
11. Gage Block Valve
12. Flow Meter Block Valve
13. Flow Meter T/C
14. Differential Pressure Flow Meter
    Test 2,3,5 and 7 Only
15. Metering Valve, Test 3 Only
16. Wet Test Flow Meter, Test 2 and 5 Only
17. Gage 0-150 psig
18. Pressure Transducer
    0-1,000 psig for Test 1,3 and 4
    0-100 psig for Test 6
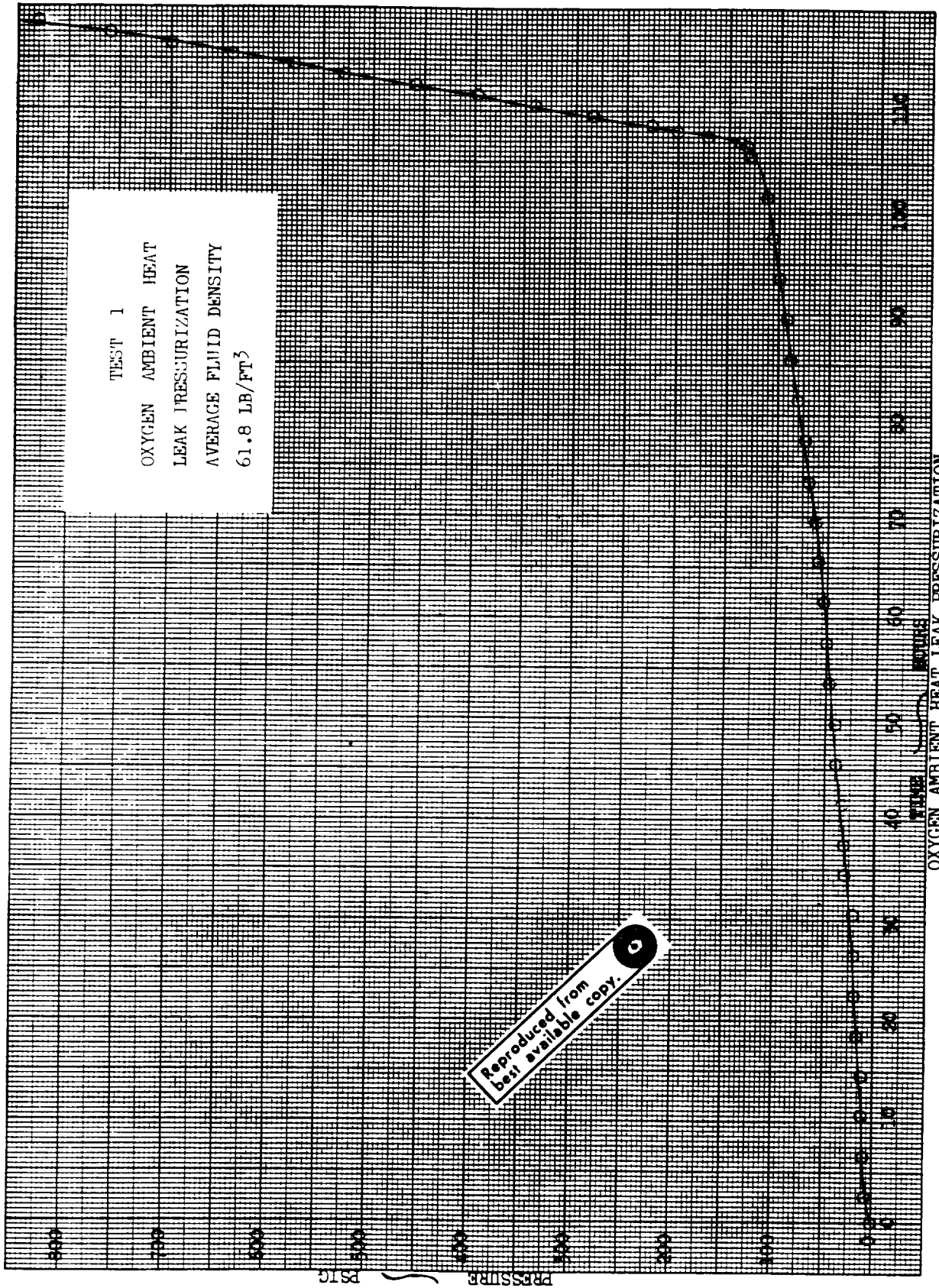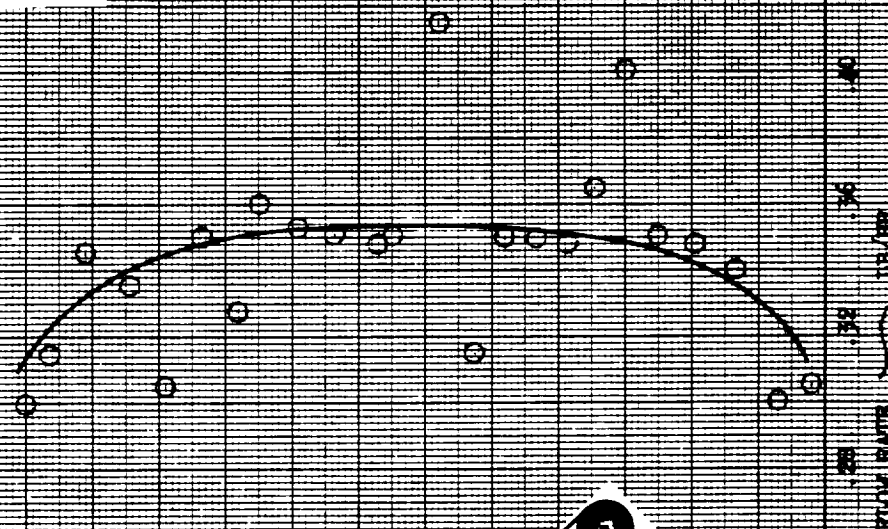   0-5 psig for Test 2,5 and 7

FLUID FLOW SCHEMATIC
FIGURE 4
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TEST 1

OXYGEN AMBIENT HEAT

LEAK PRESSURIZATION

AVERAGE FLUID DENSITY

61.8 LB/FT^3

PRESSURE PSIG

TIME MINUTES

OXYGEN AMBIENT HEAT LEAK PRESSURIZATION
FIGURE 5
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TEST 3
OXYGEN MINIMUM FLOWRATE
AT 850 psig

FIGURE 6
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TEST 4

NITROGEN AMBIENT HEAT

LEAK PRESSURIZATION

AVERAGE FLUID DENSITY

44.2 LB/FT^3

NITROGEN AMBIENT HEAT LEAK PRESSURIZATION
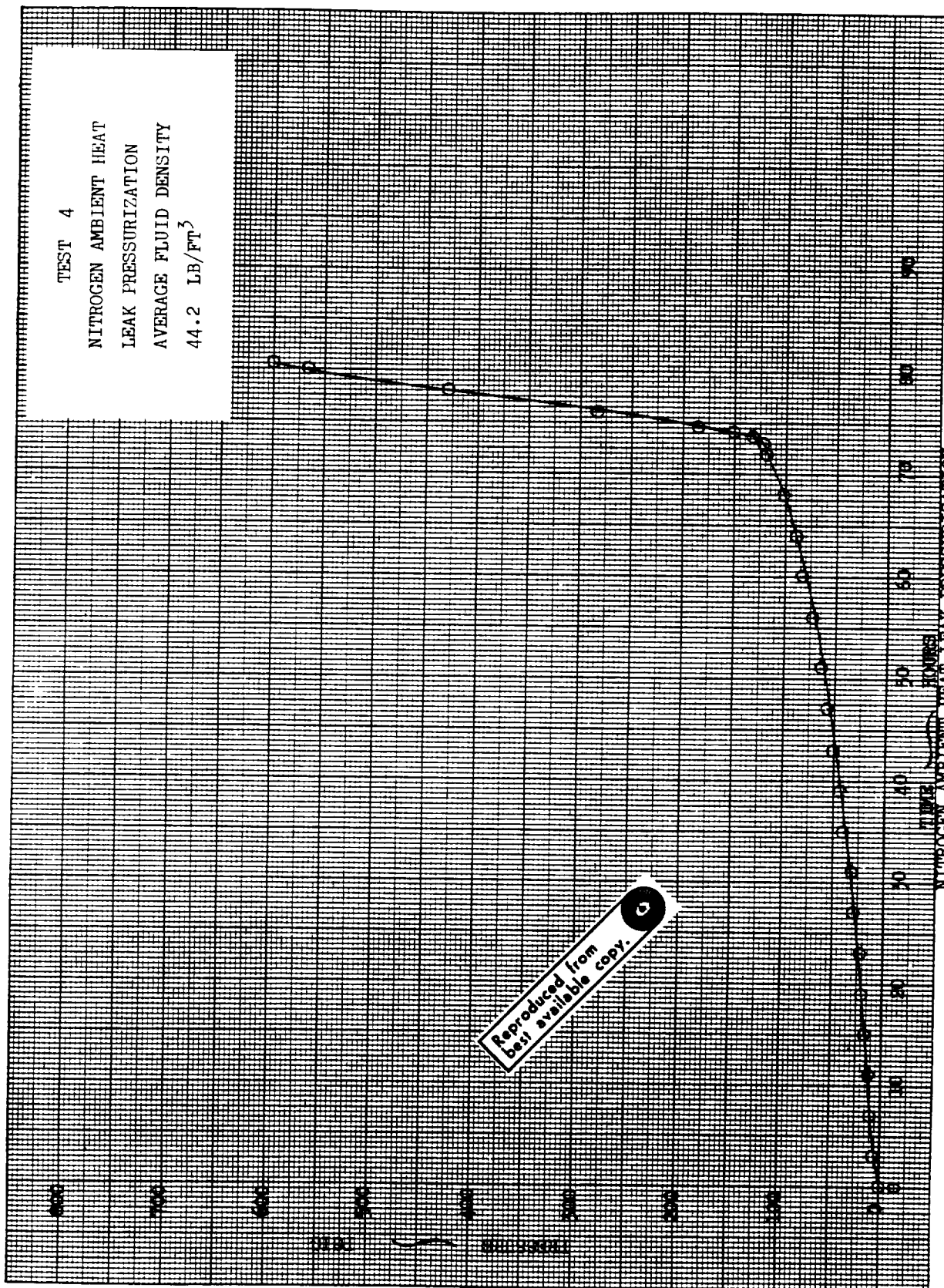
FIGURE 7

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TEST 6

HELIUM AMBIENT HEAT

LEAK PRESSURIZATION

AVERAGE FLUID DENSITY

7.03 LB/FT³

FIGURE 8

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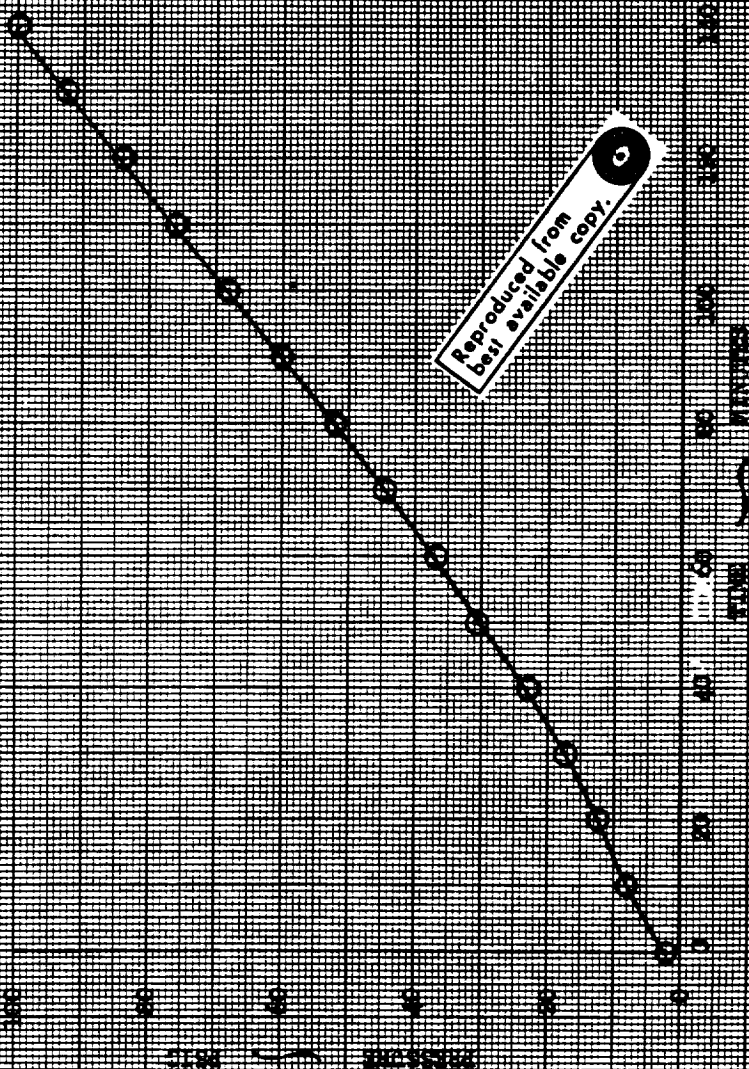FLUID TEMPERATURE VS HEAT LEAK

☐ VENTED WEIGHT LOSS TEST
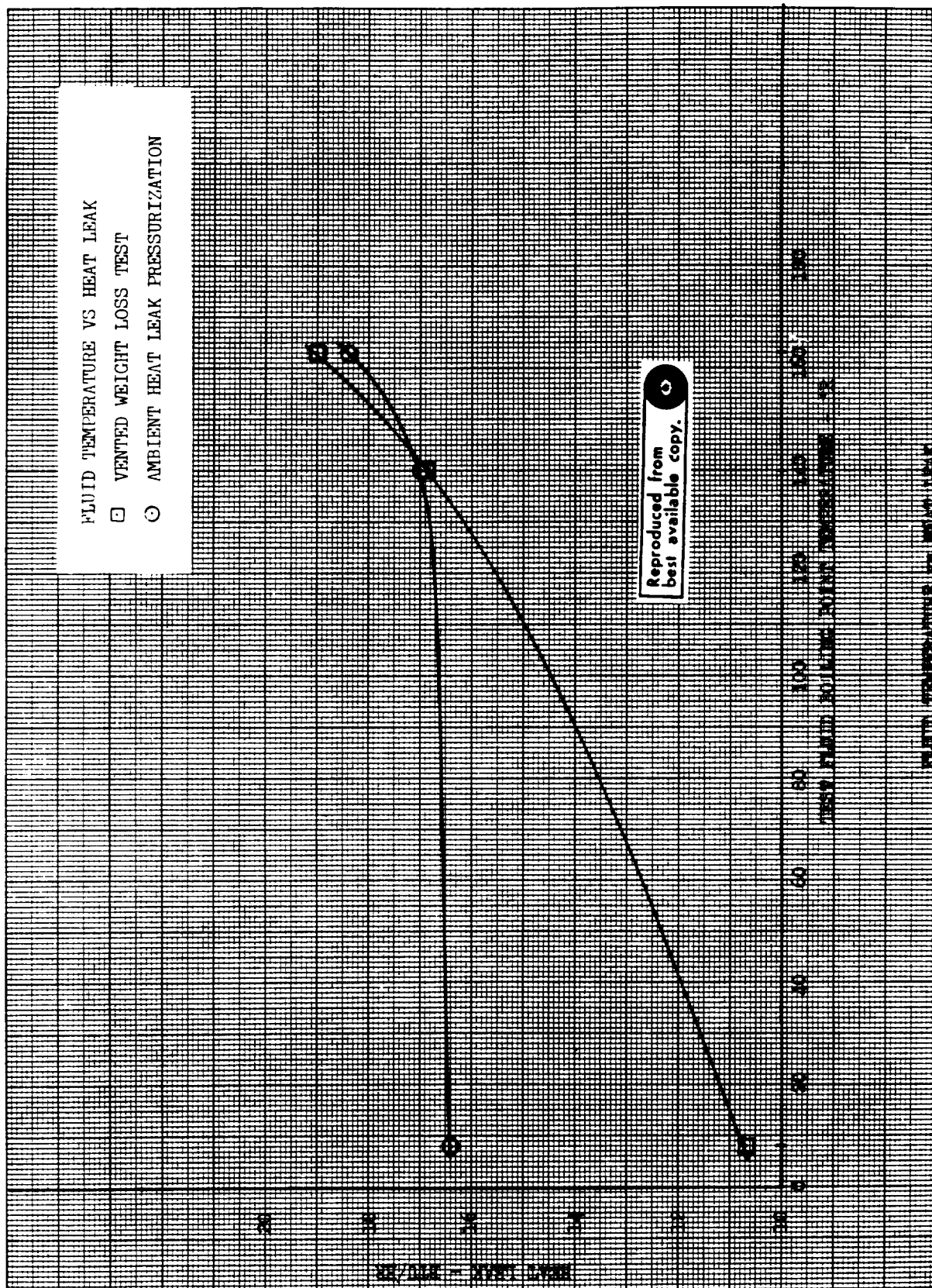
⊙ AMBIENT HEAT LEAK PRESSURIZATION

FIGURE 9
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APPENDIX

CALCULATIONS

Symbols:

u = specific internal energy (BTU/lb)

u_1 = specific internal energy of liquid (BTU/lb)

u_v = specific internal energy of vapor (BTU/lb)

U = total internal energy (BTU)

h = specific enthalpy (BTU/lb)

H = total enthalpy (BTU)

v = specific volume (ft^3/lb)

V = total volume (ft^3)

p = absolute pressure (psia)

q_m = minimum specific heat input (BTU/lb fluid expelled)

Q = average heat leak rate (BTU/hr)

ρ_v = vapor density (lb/ft^3)

ρ_1 = liquid density (lb/ft^3)

ρ_t = average fluid density (lb/ft^3)

X = quality (lb vapor/lb fluid)

L = latent heat of vaporization (BTU/lb)

$\dot{w}$ = average vapor vent rate (lb/hr)

W = total fluid weight (lbs)

J = 778 ft-lb/BTU

t = pressurization time (hours)

Test 1 - O_2 Ambient Heat Leak

$$Q = \frac{\Delta U}{t}$$

$$u_1 = h_1 - \frac{p_1 v_1}{J} \qquad u_2 = h_2 - \frac{p_2 v_2}{J}$$

$$u_2 - u_1 = \left(h_2 - \frac{p_2 v_2}{J}\right) - \left(h_1 - \frac{p_1 v_1}{J}\right)$$

$$\Delta u = h_2 - h_1 - \frac{p_2 v_2}{J} + \frac{p_1 v_1}{J}$$

Since with closed system $v_2 = v_1 = v$

$$\Delta u = h_2 - h_1 - v \frac{(p_2 - p_1)}{J}$$

$$h_1 = h_{1 \text{ liquid}} + h_{1 \text{ vapor}}$$

$h_{1 \text{ vapor}}$ = negligible at this fill density

$h_1 = h_{1 \text{ liquid}}$ (at p = 14.7 psia and T = -297°F) = 0

$$\Delta u = 24 - 0 - \frac{0.016 \ (865 - 15)}{778} = 24 - 2.5 = 21.5 \ \text{BTU/lb}$$

$$\Delta U = W\Delta u = 102 \ (21.5) = 2195 \ \text{BTU}$$

$$Q = \frac{\Delta U}{t} = \frac{2195}{119} = 18.4 \ \text{BTU/hr}$$

Test 2 - O_2 Vented Weight Loss (Considering latent heat only)

$$Q = \dot{w}L$$

$$= 0.207 \times 91.6$$

$$Q = 19.0 \ \text{BTU/hr}$$

Test 3 - O_2 Minimum Flow Rate

$$Q = \dot{w}q_m$$

$$= 0.355 \times 30$$

$$Q = 10.7 \ \text{BTU/hr}$$

Test 4 - N_2 Ambient Heat Leak Pressurization

$$Q = \frac{\Delta U}{t}$$

$$X = \frac{\rho_v \ (\rho_l - \rho_t)}{\rho_t \ (\rho_l - \rho_v)} = \frac{0.288 \ (50.5 - 44.2)}{44.2 \ (50.5 - 0.288)} = 0.0008$$

$$u_1 = (1 - x) \ u_1 + x u_v$$

$$= (1 - .0008) \ 12.58 + 0.0008 \ (88.84)$$

$$u_1 = 12.55 \ \text{BTU/lb}$$

$$u_2 = 31.22 \ \text{BTU/lb}$$

$$\Delta u - u_2 - u_1 = 31.22 - 12.55 = 18.67 \ \text{BTU/lb}$$

$$\Delta U = W\Delta u - 73 \ (18.67) = 1363 \ \text{BTU}$$

$$Q = \frac{\Delta U}{t} = \frac{1363}{80.5} = 16.9 \ \text{BTU/hr}$$

Test 5 - N$_2$ Vented Weight Loss (Considering latent heat only)

$$Q = \dot{w}L$$

$$= 0.197 \times 85.7$$

$$Q = 16.9 \text{ BTU/hr}$$

Test 6 - He Ambient Heat Leak Pressurization

$$Q = \frac{\Delta U}{t}$$

$$X = \frac{\rho_v \,(\rho_1 - \rho_t)}{\rho_t \,(\rho_1 - \rho_v)} = \frac{1.03\,(7.81 - 7.03)}{7.03\,(7.81 - 1.03)} = 0.0168$$

$$u_1 = (1 - x)\,u_1 + x u_v$$

$$= (1 - 0.0168)\,3.94 + 0.0168\,(10.66)$$

$$u_1 = 4.05 \text{ BTU/lb}$$

$$u_2 = 7.35 \text{ BTU/lb}$$

$$\Delta u = u_2 - u_1 = 7.35 - 4.05 = 3.30 \text{ BTU/lb}$$

$$\Delta U = W\Delta u = 11.6\,(3.30) = 38.3 \text{ BTU}$$

$$Q = \frac{\Delta U}{t} = \frac{38.3}{2.33} = 16.4 \text{ BTU/hr}$$

Test 7 - He Vented Weight Loss (Considering latent heat only)

$$Q = \dot{w}L$$

$$= 1.20 \times 8.82$$

$$Q = 10.7 \text{ BTU/hr}$$